



Description and validation of a " non path-dependent " model for projecting contrasting urban growth futures

Thomas Houet, Rahim Aguejdad, Omar Doukari, Guillaume Battaia, Keith Clarke

► To cite this version:

Thomas Houet, Rahim Aguejdad, Omar Doukari, Guillaume Battaia, Keith Clarke. Description and validation of a " non path-dependent " model for projecting contrasting urban growth futures. *Cybergeo : Revue européenne de géographie / European journal of geography*, 2016. hal-01326063

HAL Id: hal-01326063

<https://hal.science/hal-01326063>

Submitted on 3 Jun 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Thomas Houet, Rahim Aguejdad, Omar Doukari, Guillaume Battaia et Keith Clarke

Description and validation of a “non path-dependent” model for projecting contrasting urban growth futures

Introduction

- 1 Land change science “seeks to understand the dynamics of land cover and land use as a coupled human–environment system to address theory, concepts, models, and applications relevant to environmental and societal problems, including the intersection of the two” (Turner et al, 2007). The exploration of possible future land use and cover change (LUCC) has been identified as a key issue in land change science (Verburg et al 2004; Lambin and Geist, 2006). Anthropogenic disturbance, and more specifically conversion into urban land uses, is one of the most environmentally significant types of LUCC. Currently over 50% of the world population lives in urban areas (30% in 1950s) and the United Nations anticipates an increase to 72% by the 2050s (United Nations, 2012), further increasing the level of urban transition, especially in the developing world. Urban growth can lead to dramatic social and ecological consequences affecting, for example human mortality due to heat waves (El Abidine El Morjani et al, 2007), urban climate (Aguejdad et al, 2012), biodiversity (Forys and Allen, 2005; Clergeau et al, 2006), water resources (Tu et al, 2007) and other environmental issues (Johnson, 2001).
- 2 Projecting future LUCC is crucial to anticipate and quantify their related environmental impacts (habitat connectivity, urban heat island, etc.). It represents useful information highlighting the impacts of (un)desirable futures that may be used by stakeholders to define a consistent management strategy according to social and environmental expectations. It requires the use of computation simulations using LUCC models combined with scenarios. Numerous models have already been developed over the last two decades and used for projecting urban growth at various scales. Some are specifically dedicated to urban modeling decades (for e.g. White and Engelen, 1993, 1997; Clarke et al, 1997; Landis, 1998; Gusdorf and Hallegatte, 2007) whereas others deal with various types of LUCC (Agarwal et al, 2002; Haase and Shwarz, 2009). We choose the SLEUTH model (Clarke et al, 1997) for several reasons but the main one is its ability to reproduce various types of urban patterns (scattered, edged, along network infrastructure) and their emergence.
- 3 In the literature, two main approaches aiming at combining scenarios and models can be distinguished. The “story and simulation (SAS)” approach, formalized by Alcamo (2008) assumes that the scenarios are first defined by experts and/or participatory approaches throughout narratives. They are then translated into quantitative parameters that feed spatially explicit models whose simulated outcomes illustrate the narratives. The opposite approach assumes that simulated outcomes provide quantitative scenarios. Various modeling techniques can be used for these two main approaches aiming to explore the future. In any case, it is recognized that the SAS approach allows to explore a wider diversity of futures, with contrasted / breaking trends scenarios. Such forecasts have been shown to be important for creative scenario-based land use planning (Xiang and Clarke, 2003). LUCC models exhibit more or less ability to simulate a wide diversity of futures due to their design and architecture, especially those that are path-dependent (Brown et al. 2005). Whatever the approach adopted, the question of model’s validation is crucial when combined with scenarios. While the model’s calibration allows to validate the simulated outcomes under a path-dependent approach, the question remains for the SAS approach: how can we validate such a model although the calibration may constrain its ability to explore a wider range of futures?
- 4 The objective of this paper is twofold: (1) to present an urban growth simulation model, derived from the SLEUTH modeling framework, specifically dedicated to simulating contrasting /

breaking trends scenarios accordingly to the “storyline and simulation” approach; (2) to propose a validation framework aiming at demonstrating the ability of the model to simulate such kind of scenarios according to Houet (2015). We assume it goes beyond conventional validation procedures by focusing on assessing the model’s ability to simulate observed changes as well as contrasted – and potentially unrealistic – futures. The first part of the paper (section 2) exposes the reason why the SLEUTH* model has been developed. It proposes a review of modeling techniques usually combined with scenarios and claims for the need for “non path-dependent models” when the SAS approach is adopted. Then, it presents the SLEUTH experience and challenges. The second part (section 3) lists the materials and methods: it describes the study area, input data and the SLEUTH* model. Section 4 focuses on the validation experiments and results to validate the model’s ability to simulate contrasting / breaking trends scenarios. Section 5 illustrates an application of SLEUTH* to explore futures based on three contrasting scenarios. The final part discusses the validation approach and compares the respective limitations and drawbacks of SLEUTH and SLEUTH*.

State of the art

The need for non path-dependent urban growth models for prospective and forecasting

- 5 Two contrasting and complementary modeling approaches can be distinguished based on the definition of path-dependent models (Brown et al., 2005). First, we assume the path-dependent approach aims at mimicking past land changes into the future based on the calibration phase on a past period, using internal models functionality as described by Mas et al. (2014). The model estimates LUCC quantitatively using at least two land use / cover maps as inputs to detect and simulate trends. Various amounts and rates of LUCC can be computed in order to produce different scenarios. For example, some models use Markov chains or probability matrices computed from the input maps to estimate future LUCC by extending the observed trend forward to a greater or lesser degree. The estimation of suitable LUCC land allocation is computed based on the comparison of driving factors with the observed LUCC (Kolb et al, 2013) using logistic regression or artificial neural nets for example. In these forecasts, the influence of the driving forces is not usually modified during the simulation. Models also offer the ability to assess various land management / preservation options by incorporating incentives/constraints maps and/or future roads development. Finally, such approaches assume an equilibrium state within the study area during the model calibration and simulation phases. These models are particularly suitable for simulating trend-based scenarios, i.e. where LUCC quantity, allocation and processes do not differ significantly from past changes, with the capacity to explore various alternative land management/preservation options.
- 6 Secondly, a non path-dependent approach assumes that LUCC models are used to spatially explicitly render a set of pre-defined contrasted scenarios. They are inherently used within the SAS approach. Path-dependent models can be used within the SAS approach as well. In this case, the parameterization of the future land demand does not depend on input maps used to calibrate the future amount of changes. Some studies illustrate this approach (e.g. Price et al, 2014; Verburg et al, 2008) as the land demand is defined by narratives and/or economic model outcomes. However, this kind of models use suitability maps to allocate future changes that are defined by comparing past changes (occurred during the period covered by these two input maps for instance) with spatially explicit drivers (such as the elevation, the slope, or the distance from a land cover) using statistical method. Since the allocation of future land changes depend of suitability maps, the allocation remains path-dependent while the land demand is not. The term ‘scenario’ refers here to the definition given by Xiang and Clarke (2003) for land use planning, characterized by five components: alternatives, consequences, causations, time frames and geographical footprints. They are built using various robust and rigorous methodological approaches (Amer et al., 2013) based on ‘intuitive logics’ (Wack, 1985a, 1985b), ‘probabilistic modified trends’ (Bishop et al., 2007) or on the ‘scenarios’ method’ (Godet, 1986). These scenarios are then instantiated by qualitative and/or quantitative

parameters throughout narratives and/or model-based projections. The narrative is the plan that explains how the present becomes the future, and that relates directly to some manipulation of the model or its parameters, and the projections can be chosen to encourage creative thinking during the scenario-based planning process. Hence, considering that these kinds of scenarios are deliberately imaginative, some of these models may have computational limitations for simulating various types of scenarios as they were simply not initially developed for that purpose. Moreover, the urban system under study will not remain stationary over time. New driving forces may affect the quantity, types, location and/or the patterns of LUCC. Some of the previously cited models may be used in such an approach since the land demand and/or the suitability maps are from scenarios or models' outcomes. Nevertheless, the theoretical distinction between SAS vs. path-dependent approaches remains unclear when path-dependent models are used within a SAS approach. Their calibration is made using historical land use and land cover maps to define LUCC transition rules and inherently assume the system to be stationary. Finally, some existing LUCC models have inherent constraints that prevent them from simulating future contrasted scenarios that assume or create a ‘break’ with the past or current trend (Mas et al., 2014).

- 7 Path-dependent and SAS approaches illustrate two ways in which scenarios can be produced and implemented (Marchadier et al., 2012). In the first case, scenarios are inherited from a numerical – quantitative – modeling approach with prescribed rules for producing simulated cities. In the second case, scenarios are based on a narrative – qualitative – approach producing imagined cities. Approaches combining both narrative and model approaches for building scenarios are not so common whereas they are fundamental to land-use planning (Xiang and Clarke, 2003). Moreover, the use of models adds value to qualitative prospective studies (Kok et al., 2007a; Houet et al., 2010a) because: (1) they are helpful for participatory approaches (Kok et al., 2007b) and are an illustrative means for the ‘bridging’¹ function of scenarios (Xiang and Clarke, 2003); (2) they provide realistic simulations of future LUCC which are helpful in understanding landscape dynamics and assessing and understanding the possible impacts of different urban development strategies (Aguejdad et al., 2012); and (3) they reduce future uncertainty by exploring a wide diversity of future LUCC conditions (Verburg et al., 2010).
- 8 A non path-dependent approach questions the usefulness of the model calibration process which is usually a mean to validate the model. One of the most common approaches to validate such models consists of using indicators generated from a comparison between simulated maps and an observed map (Pontius et al., 2008; Gaucherel et al., 2008; Paegelow et al., 2014). These indicators are particularly valuable for assessing the model's ability to simulate the past evolution of a landscape. However, the question of validating a simulation whose narrative aims to project future LUCC that break out of prior LUCC trends (termed here a ‘trend breaking scenario’) remains. How can the degree of confidence in the simulations be assessed while: (a) a calibrated model would inherently reproduce past trends in terms of land demand and/or land use change; (b) the future is unpredictable, especially the distant future; and (c) a prospective scenario does not aim at being a prediction or forecast, since its purpose is to encourage thought. This question is not addressed directly in this paper, but we assume that results from various types of simulations (sensitivity tests, simulations over a past period or of contrasting future scenarios) may help to increase the users and stakeholders' confidence in the model's capacity to spatially explore the future (Houet and Gaucherel, 2007; Houet et al., 2014). Their plausibility depends on how the scenarios have been built and accepted by the stakeholders and participants, i.e. whether the principles of the scenarios' methodology has been respected to define the narratives (Godet, 1986). Conversely, a LUCC model may contribute to make the scenarios implausible if the model is not able to simulate the spatial and temporal dynamics (rates, types and direction) of LUCC defined in the storyline. The use of experiments could contribute to improving users respect for the transparency and consistency criteria of the prospective approach (as defined by Godet, 1986) and thus validating model's ability to simulate plausible future states and dynamics accordingly to scenarios.

- 9 An application is conducted on an urban area located in France exhibiting fast demographic growth. The SLEUTH has been chosen (Clarke et al, 1997) for its ability to simulate various types of urban patterns (scattered, edged, along network infrastructure) and their emergence.

The SLEUTH experience and challenges

- 10 SLEUTH is a cellular automaton model simulating urban growth dedicated to land use policy and decision-making processes. The long-term goal of the project is to develop these tools to best predict urban growth on a regional, continental and eventually global scale. The name SLEUTH was derived from the simple image input requirements of the models: Slope, Land cover, Exclusion, Urbanization, Transportation, and Hillshade. It has been extensively described in the literature (Clarke et al, 1997; Clarke and Gaydos, 1998; Clarke, 2008; Chaudhuri and Clarke, 2013) and used for numerous applications in cities over the world (Silva and Clarke, 2002; Jantz et al, 2003; Yang and Lo, 2003; Dietzel et al, 2004; Dietzel et al, 2005; Clarke et al, 2007). How SLEUTH works has been summarized by Clarke (2008) and is presented in the following box (box 1). Putting aside its international recognition, we selected SLEUTH for four reasons:

- the open-source code allows it to be modified for a non path-dependent approach (<http://www.ncgia.ucsb.edu/projects/gig/>);
- the availability of experiences and feedbacks that have explored the model and its use (Clarke et al, 2007; Clarke, 2008; Chaudhuri and Clarke, 2013);
- its reliability with regard to environmental and participatory issues, due to its relative simplicity and pattern-based characteristics (Suarez-Rubio et al., 2012);
- its capabilities to simulate various urban growth patterns and emergent phenomena (Silva and Clarke 2005).

Box 1: Summary of the SLEUTH's functioning.

SLEUTH is a model for the computational simulation of urban growth and the land use changes that are caused by urbanization. Four rules mimicking possible urban growth patterns (spontaneous, new-spreading centers, edge growth and road-influenced) can be successively applied at each time-step. Five parameters influencing the respective weight of these rules are determined after a calibration process using historical and/or remotely sensed urban maps. They set SLEUTH's behavior to project urban growth using a Markovian cellular automaton (Candau et al 2000). A first set of three parameters allows controlling the pattern of urban growth: the *diffusion* algorithm allows to simulate scattered small urban patches while the *new spread-center* does the same with urban patches exhibiting a critical size from which can emerge villages or cities; the *edge-growth* extends existing urban patches. A further parameter simulates the attraction of new urban development towards roads (*road-influenced* growth). These parameters are inter-related. For example, when development is attracted to a road by the road gravity factor, urbanization along the road network can be relocated in proportion to the diffusion/new-spread/edge-growth proportions (Clarke 2008). A final parameter defines the resistance of urbanization to spreading up steep slopes (slope). In addition, urban planning options can be incorporated into the model as input maps to preserve strategic areas from urban growth (excluded map). This data set and parameters are the foundation for simulating scenarios using SLEUTH. The use of this type of data could vastly improve forecasts (Onsted 2007) and could enable urban growth impacts to be evaluated (Clagget et al 2004; Solecki and Oliveri 2004). This data set can be generated from an expert-knowledge approach as well as modeling tools generating various scenarios with distinct social, economic and demographic assumptions (Onsted 2002).

The calibration phase is critical and delicate as it strongly depends on the historical maps used and their resolution. Calibration has constituted one of the main issues of previous works. It has been considerably improved using efficient algorithms and methods (Goldstein 2004a)

that challenged the computation time initially required and the refinement of model parameters that replicate the best historical changes (Dietzle and Clarke 2004). Moreover, it has been shown that refining spatial resolution increases model sensitivity to local conditions (Silva and Clarke 2002). SLEUTH is a robust model largely explored through sensitivity tests (Candau 2002; Dietzle and Clarke 2004; Goldstein et al 2005). Unresolved issues and problems have been highlighted by Clarke (2008). Details on algorithms and parameters used are presented in the tutorial provided with the SLEUTH* software.

- 11 Many challenges remain when using SLEUTH within a non path-dependent approach. As mentioned by Clarke (2008), an important purpose of modeling with SLEUTH is to relate to policy and the decision-making process. Recent efforts to use SLEUTH for these issues have been made. For example, Mahiny and Clarke (2012) incorporated a Multi-Criteria Evaluation approach in the modeling process for land use planning purposes in Iran. Incorporating a suitability map in the excluded layer (cf. box 1) is particularly helpful to assess any desired or undesired planning strategies. Results show that this approach is better for simulating future urban patterns according to the defined scenarios. In the same way, the excluded layer can be used to incorporate information on the degree to which a cell attracts or repels urban development (Jantz et al 2010). Yet SLEUTH still faces some limitations. As an example, for the model output to be effective in scenario planning, the time required to run the model, due to the time-consuming calibration phase, can limit its effectiveness in participatory scenario studies (Clarke 2008). Moreover, its calibration may limit the simulation of trend breaking scenarios by replicating observed LUCC trends, in terms of magnitude, due to the Markovian process, and the urban pattern growth as reflected in the historical maps used for calibration.
- 12 We seek to extend the usability of SLEUTH for urban/land planning under a scenario-based approach where the predefined scenarios anticipate disruptions of LUCC trends, i.e. they may exhibit non-linear changes in the urban dynamics (rates and patterns) over time, at specific user-defined dates that have potentially not been observed in the past. The modified version of SLEUTH (hereafter called SLEUTH*) tackles the following issues:
- the calibration is inactivated and the simulation is driven in a fully controlled mode with parameters defined by a scenario describing future urban rates and patterns;
 - SLEUTH behavior (elementary algorithms) is preserved though its functioning and initial parameters are adapted and extended;
 - a scenario is generated using either user-defined parameters or a tightly coupled external model;
 - the development of a user-friendly interface aims at facilitating its use for scientific, professional and/or educational purposes, consistent with scenario-based planning.
- 13 SLEUTH* has been developed for the ACCLIMAT project² (Adaptation to climate change of the urban area of Toulouse, France) to assess the impacts of land planning and climate change scenarios on urban climate (Masson et al, 2014). SLEUTH* was applied to the Toulouse metropolitan area (South West France) where urban growth strongly influences urban climate, particularly urban heat islands (Masson et al., 2008; Houet and Pigeon, 2011; Aguejdad et al., 2012).

Materials and methods

Study area and input data

- 14 The urban area of Toulouse is located in South West France (43°36'17"N; 1°26'42"E) in the Midi-Pyrenees region and is composed of 342 municipalities, with 75,000 ha of urban areas and 1.13 million inhabitants in 2008 (Figure 1). Toulouse is currently one of the most attractive urban areas in France in terms of new inhabitants, economy and well-being. The study area is a rectangle of 84 x 94 km encompassing the metropolitan area. Demographic growth has been +14,000 newcomers per year between 1990 and 2006 leading to a strong increase of artificial surfaces (+1,300 ha/year) over the same period. The model inputs are similar to those commonly used with SLEUTH and are summarized in figure 2. All input maps feature a cell

size of 100*100 meters. Land use maps were made by the classification of Landsat satellite imageries and aerial photographs. Slope and hillshade maps were derived from ASTER DEM data (<http://gdem.ersdac.jp/space/systems/or.jp/>). Excluded areas and transportation maps were provided by the French National Geographic Institute and/or derived from land management plans. The attractiveness map (A1, Fig. 2f) presented here is a modeled outcome (presented in § 2.3.3.) expressing the urban attractiveness using the distribution of rental prices.

Figure 1 -Toulouse location and land use and cover maps in (a) 1990 and (b) 2006 with four classes: urban (red), agricultural land (light green), woodland (dark green) and water (blue).

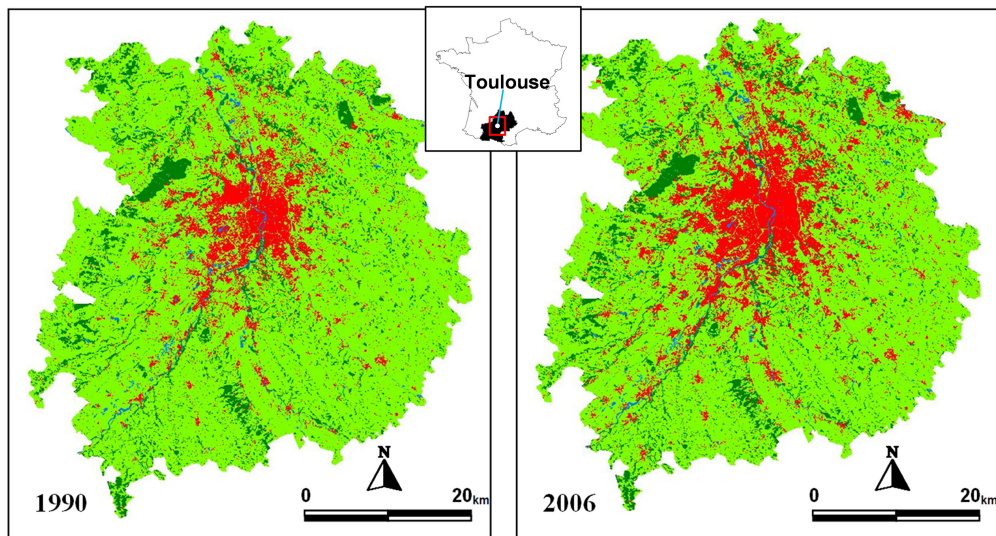
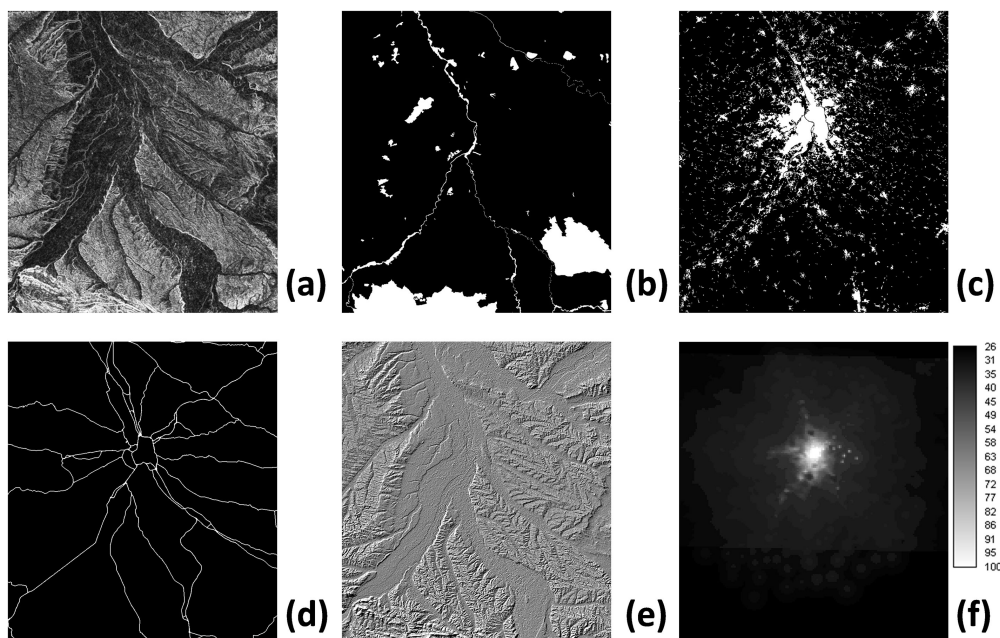


Figure 2 - Input data for SLEUTH* (84 x 94km): (a) Slopes map - light grey represents steep slopes; (b) Excluded map - protected and flood control areas and those outside the study area are in white; (c) Urban map for 2006 (white); (d) Transportation network map - only major roads have been used (white); (e) Hillshade map; (f) Attractiveness map (from 0 -low - to 100 - high - attractiveness)- A1.

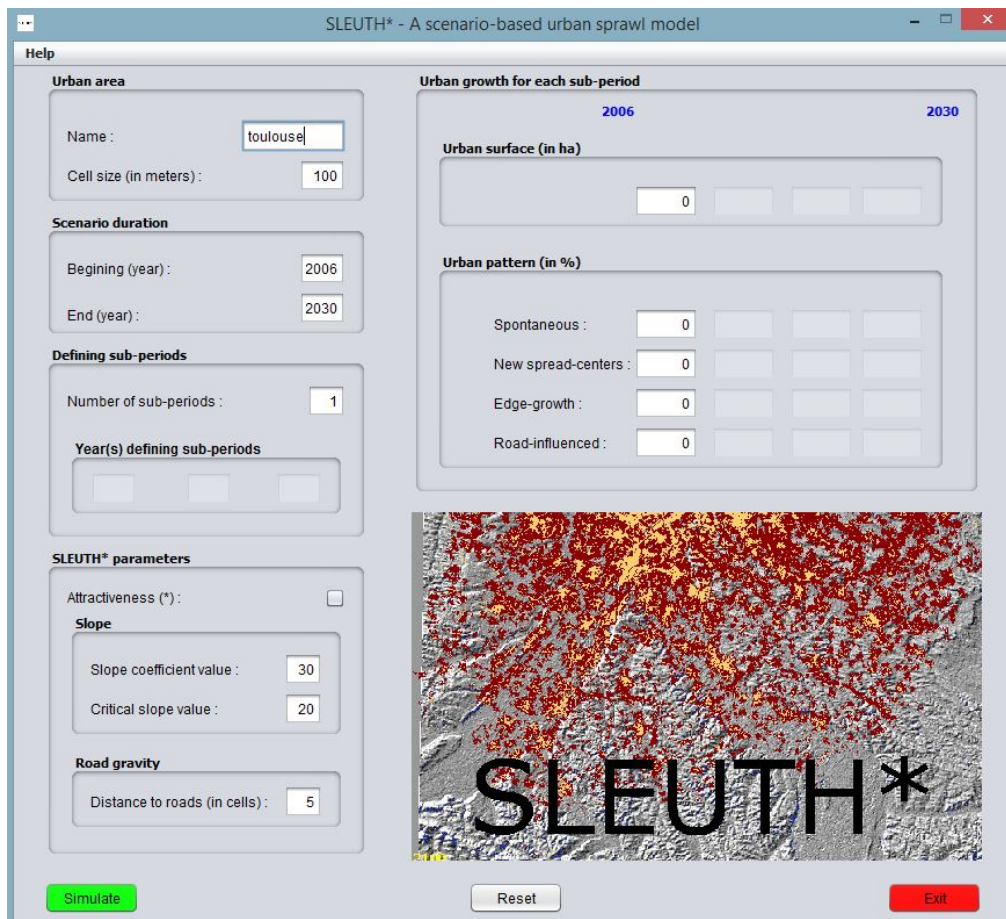


SLEUTH* software: A scenario-based design incorporating a new spatial driving factor (*)

- 15 SLEUTH* has been developed from SLEUTH version 3.0 with the following objectives: (1) to be used for simulating scenarios with possible trend breaking LUCC behaviors; (2) to be used independently or tightly-coupled with an external model contributing to the scenario parameterization; (3) to be user-friendly through the development of a user-friendly interface

improving model understanding, usefulness and benefits for users, including land planners and students (Figure 3). SLEUTH* is distributed as freeware³ and delivered with tutorials and details on its functioning.

Figure 3 - SLEUTH* software interface



- 16 The first main step is to define various patterns and magnitudes of urban growth divided into sub-periods. For each sub-period, the future extent of urbanization (in hectares) and urban pattern parameters are empirically set up. This enables full control of the urban growth defined by narrative scenarios or the external model's outcomes. Thus, the SLEUTH* growth parameters (spontaneous growth, new spread centers, edge growth and road-influenced) each make their respective contribution (in % of the amount) to urban growth.
- 17 The second main step is to integrate an additional spatially explicit factor that can influence urban growth as a seventh input map, called '*'. As different areas can be more attractive under specific scenario assumptions, due to land prices and/or accessibility, it was necessary to add a factor that highlights the land's attractiveness. This is complementary to the *excluded* factor that forbids or slows urban growth in future user-defined scenarios. The '*' parameter, called 'Attractiveness' in the SLEUTH* interface, aims at representing a land suitability map and may be obtained from an external model or from an expert-knowledge approach as in Mahiny and Clarke (2012). Its integration can be activated or not by the user. Hence, this additional input is optional and does not alter the original version of SLEUTH when disabled. Its implementation is similar to how the slope input is taken into account: values are filtered and ranked using a linear function. The candidate cells for urbanization identified from the corresponding map are then sorted (i.e. where probability is the highest). Those where the attractiveness is the highest are randomly urbanized until the amount of change is reached.
- 18 The third objective is to use the other parameters, as SLEUTH does by default, when they are necessary. The resistance of the terrain (slope parameters) remains modifiable for each city but is assumed to be constant over time. The road gravity constant (distance in cells from a road that influences urban growth) can be modified by users. The cell size can be defined in order

to use SLEUTH* with data at various resolutions. Last but not least, excluded, transportation and attractiveness maps can be manually updated during the simulation⁴.

Model validation

- 19 The validation procedure consists in assessing the model’s ability to: (1) efficiently simulate an urban expansion that is similar to an observed situation using empirically defined parameters; (2) simulate a scenario with trend breaking LUCC behavior; and (3) spatially explicitly project long-term contrasting scenarios made using a participatory planning approach and model coupling. The first experiment obey to the conventional validation procedure comparing simulations *versus* a known situation to increase the confidence users can have in its ability to mimic past land use and cover trends. It slightly differs from an approach using a self-learning calibration procedure as the input parameters have to be user-defined when co-constructing scenarios. However, this first experiment does not validate the model capacity to simulate non path-dependent changes. This is the aim of a second experiment aiming at simulating a trend breaking scenario. Because we did not modify the way SLEUTH functions, tests focused on the specifics of SLEUTH*. Slope parameters were set to 30 and 20 for the slope coefficient and critical slope respectively and the distance of influence of roads set to 5 pixels. These parameters remain unchanged over the various simulations made. Each experiment was run 30 times. Variations are shown in graphs using specific indicators. As variations are small, the spatial analysis of urban growth is made for one simulation.

Experiments Design

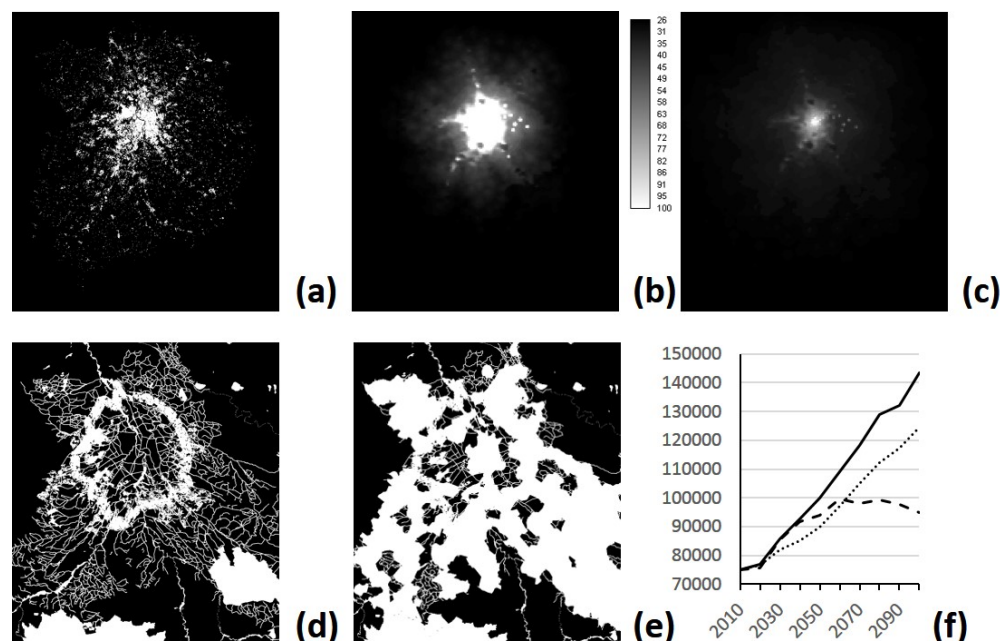
- 20 The first experiment hypothesizes that SLEUTH* can be validated for simulating expected future LUCC if it is able to replicate a plausible urban landscape using historical /observed maps. A scenario was defined based on the urban changes that occurred between 1990 and 2006. Urban pattern parameters were empirically determined using GIS and landscape metrics. Based on the map of urban changes, it is possible to approximate which proportion of the changes are located near roads or existing urban land use in 1990. It is assumed that the remaining part depends on both the “spontaneous growth” and the “new spreading centers” growth parameters. Urban patch size (in cells) allows us to differentiate their respective contribution: patches greater than one cell are assumed to be generated by the new spreading centers parameter. This simple method, which cannot distinguish the merging of small urban patches with bigger, leads to the following approximate combination for growth during 1990-2006: 3% spontaneous growth, 11% new spread centers, 83% edge-growth and 3% road-influenced growth. These amounts were then applied to the historical map with SLEUTH*.
- 21 Several landscape metrics (Number of Patches (NP), mean distance between patches (DP) and the patch size standard deviations, the mean area of urban patches (PA) and its standard deviation, Cohesion (Co) and Clumpiness (McGarigal and Marks, 1995), describing urban landscape pattern, were computed from the simulated results. The patch cohesion increases as the patch type becomes more clumped or aggregated in its distribution; hence, more physically connected (Gustafson, 1998). Because these metrics are independent of the way SLEUTH* functions, they can be used to verify whether the model is able to simulate a scenario (Mahiny and Clarke, 2012) over a past period. An additional method was used in the assessment. Maps of pixel-by-pixel differences between simulated and observed maps for 2006 were computed for assessing the location disagreement (Pontius 2000, 2002), i.e. showing errors of omission and commission. The simulations (S1) used the land cover map of 1990 as the input map. They then run until 2006 and the output maps were compared with the observed 2006 map. S1a and S1b allow for a comparison between SLEUTH* (with the attractiveness A1 map) and SLEUTH (without) with the same parameterization, whereas S1c constitutes a baseline scenario with ‘neutral’ parameters, i.e. with urban parameters set to 25% in order to assess whether S1a and S1b differ or not from a neutral simulation. Parameters used are summarized in table 1.

Table 1 - Summary of the validation experiments. The inputs parameters of SLEUTH* are described for each simulation / scenario. Cited excluded and attractiveness maps are described in figure 4.

Objective / Simulation	Time periods	Urban growth patterns (in %)				Quantity of urbanization (in ha/year)	Excluded map	Attractiveness map
		Spontaneous	New spread centers	Edge	Road influenced			
Simulating a past evolution								
S1a	1990-2006	3	11	83	3	1282	E1	A1
S1b	1990-2006	3	11	83	3	1282	E1	-
S1c	1990-2006	25	25	25	25	1282	E1	A1
Simulating a trend breaking scenario								
S2	2006-2030	10	5	80	5	1300	E1	A1
	2030-2070	100	0	0	0	800	E1	A2
	2070-2100	0	0	100	0	1500	E2	A3

22 To ensure that the model is able to deal with trend breaking LUCC, a second experiment (S2) is defined. A scenario exhibiting contrasting changes in terms of land demand, urban patterns and land planning strategies (excluded maps) is defined and simulated. The retained assumptions were exaggerated for the sake of the demonstration. Three sub-periods were defined: the first period (2006-2030) favors rapid growth (1300 ha/year) pursuing the observed trend where the center of the metropolitan area is the most attractive. The second period (2030-2070) favors a lower urban growth rate (800 ha/year) with a more scattered pattern. Municipalities located further away from Toulouse city and its surrounding municipalities become increasingly attractive considering the attractiveness of rural areas (Attractiveness map A2 – Fig. 4b) but still remain less attractive than Toulouse. The third period (2070-2100) is characterized by strong and contiguous growth (1500 ha/year) with an ‘ecological’ urban planning strategy preserving corridors (excluded map E2 – Fig. 4d). In parallel, the peak oil scenario induces a strong increase in transportation costs reducing the attractiveness of rural municipalities (Attractiveness map A3 - Fig. 4c). The input parameters are summarized in table 2. Urban dynamics are illustrated by simulated urban maps and were monitored over the 2010-2100 period by using various spatial metrics: the overall urban area (in ha), the number of urban patches (NP), the mean urban patch area (PA) and its standard deviation in hectares (ha), the mean Euclidean distance between urban patches (DP) and its standard deviation (in meters).

Figure 4 - Additional maps used for the scenarios: (a) Urban area (white) in 1990, (b) Attractiveness map - 'A2'; (c) Attractiveness map- 'A3'; (d) Excluded map - 'E2'; (e) Excluded map - 'E3'; (f) projected urban areas (in ha) with the external economic model (NEDUM) based on the three prospective scenarios Passive (plain line), Green (dotted line) and Reactive (dashed line).



Results from these two experiments are presented in the following two sub-sections.

Simulating the past evolution of urban growth (experiment S1)

The landscape metrics obtained from simulations S1a, S1b and S1c and compared to the 1990 and 2006 observed situations are shown in Table 2. It aims at evaluating the ability of SLEUTH* to mimic a past evolution.

Simulations S1a and S1b show a greater number of urbanized patches (respectively 4718 and 4640) than for 2006 (4257) and 1990 (4380) with small variations (approx. +/- 22 patches). This directly influences the mean distance between patches that is closer to the value observed in 1990 (360.6 m) for S1a and S1b (358 +/- 28 m and 363 +/- 30 m respectively) compared to 2006 (334 m). The mean variation encompasses the value of 2006 although those from the neutral simulations strongly differ. Results are obtained for the mean patch size (PA) show great similarities between the observation in 2006 and the simulations S1a and S1b. Results from S1a are closer than those from S1B. The Cohesion and Clumpy indices show similar results. Comparison with S1c (null model) shows that results obtained from simulation S1a and S1b are closer to the observed 2006 values than those provided by randomness. The resulting urban landscapes are more similar to those of 2006 than 1990 and the neutral modeled landscape meaning that SLEUTH* conveniently reproduce observed urban patterns

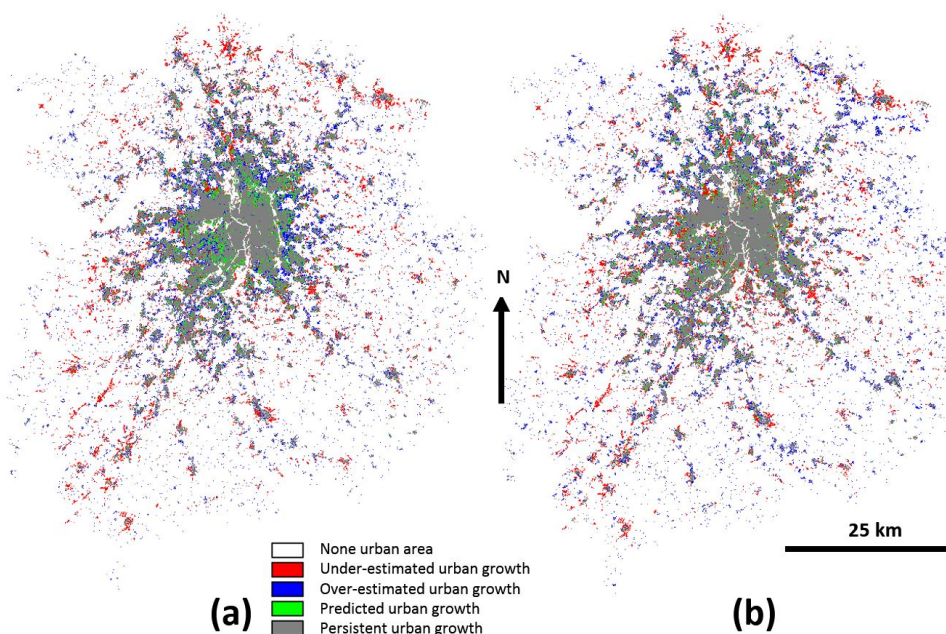
Table 2 - Comparison of simulated and observed urban areas using landscape metrics. Number of urban patches (NP), urban patch density (PD), mean patch area (PA) and its deviation (in ha), mean distance between urban patches (DP) and its deviation (in meters), Cohesion (Co) and Clumpy (CI) indices. The deviation are computed from the 30 simulations made for each simulation.

Urban map	Spatial indices				
	NP	PA	DP	Co	CI
1990 (observed)	4380	9.2	360.6	97.15	0.598
2006 (observed)	4257	14.1	334.1	97.77	0.659
Simulation with A1 (S1a)	4718 +/- 23	13.8 +/- 0.9	358.3 +/- 26.5	98.22 +/- 0.07	0.687 +/- 0.042
Simulation without A1 (S1b)	4640 +/- 21	13.2 +/- 1.2	363.3 +/- 30.4	97.85 +/- 0.09	0.668 +/- 0.064

Neutral Simulation (S1c)	9727 +/- 943	6.3 +/- 4.5	292.1 +/- 132.4	96.74 +/- 0.41	0.519 +/- 0.098
--------------------------	--------------	-------------	-----------------	----------------	-----------------

26 The pixel-by-pixel difference maps between simulations (S1a and S1b respectively) and the 2006 map are shown in figures 5a and 5b. They respectively exhibit 30.6% and 26.8% of correctly predicted urban pixels. Urbanization is better predicted in S1a in the central part of the study area while the simulation of urban growth is better in remote areas for S1b. Conversely, these simulations respectively over-estimate and under-estimate in the central area. The attractiveness map slightly improves the predictive power of SLEUTH* over the past period, but when this map is not considered, the urban pattern still remains good. Adding an additional help to improve its predictive power, i.e. the credibility end-users may have in the simulated outcomes, and the flexibility of future urban changes according to changes of settling choices of the society.

Figure 5 - Difference maps between observed urban extent in 2006 and the simulated urban growth for 2006 (a) using the attractiveness map A1 and (b) without using the attractiveness map A1. Four classes can be distinguished: persistent urban of 1990 (grey), correctly predicted urban areas (green), over-estimated urban growth (simulated while not existing - blue) and under-estimated urban (not simulated areas while existing - red).



Simulating a trend breaking scenario (experiment S2)

27 Results from the second experiment show that SLEUTH* is able to simulate non path-dependent urban changes although some existing models would not (Houet and Hubert-Moy, 2006; Mas et al, 2014). When the main trend of urban growth rates assumes a linear increase (Fig. 7a), the result shows that the model is able to cope with accelerating /decelerating rates of urban change and with contrasting dynamics of urban patterns, as illustrated by the simulated maps (Fig. 6). According to the scenario, results show that SLEUTH* is indeed able to simulate “trend breaking” urban pattern changes. For example, the increase of the number of urban patches from 2030 to 2070 involving a higher rate of spontaneous growth (from 7,100 to 26,000 patches - Fig. 7b) is then followed by a decrease of the number of patches (from 26,000 to 22,000 – Fig. 7b) due to the 100% edge growth. This trend breaking of urban patterns during the simulation can be observed as well with the mean patch area (Fig. 7c). Indeed, while the urban growth is characterized by small and scattered patches over 2030-2070 decreasing the mean distance between patches (Fig. 7d), urban growth exhibits a contrasting dynamic after 2070, characterized by the growth and the merge of existing patches. Stochastic processes do not strongly affect the results: the mean variations (error-bars in Fig. 7b, 7c and 7d) obtained

from the 30 simulations made are small and do not affect the urban trends. In others words, trend-breaking are under control by the model and does not inherit from randomness.

Figure 6 - Time series of urban sprawl based on the “breaking trends” scenario

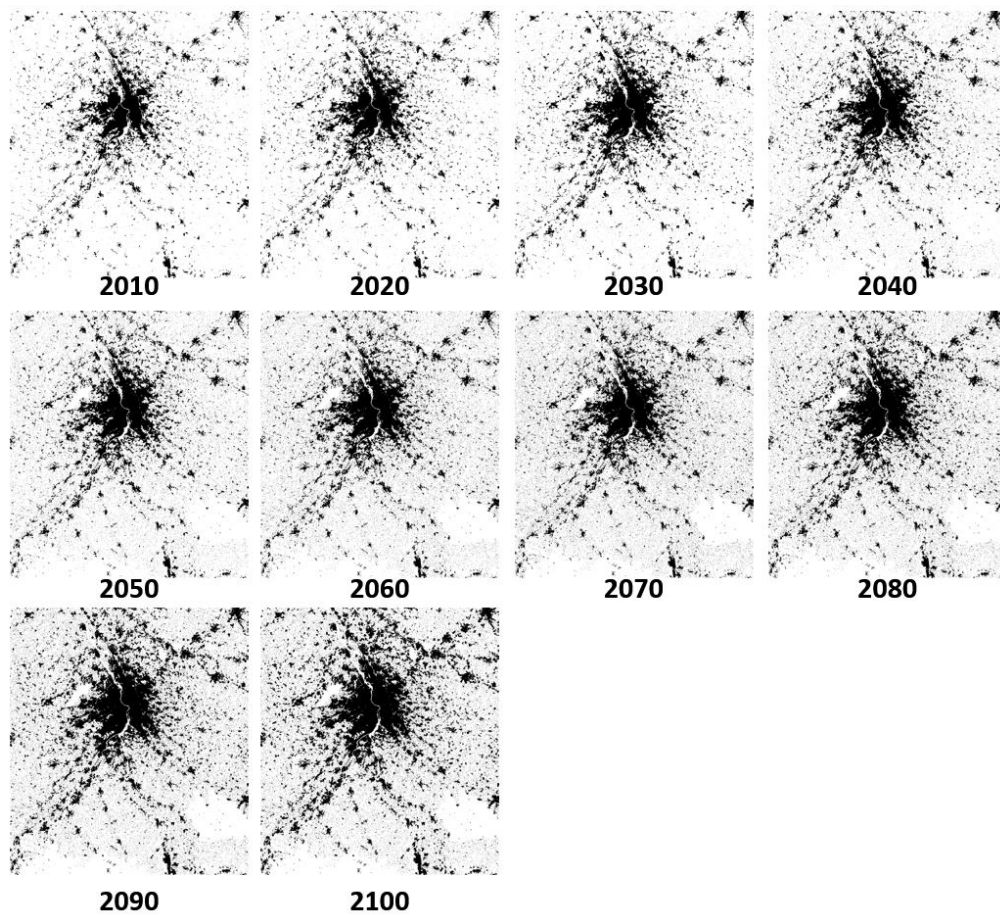
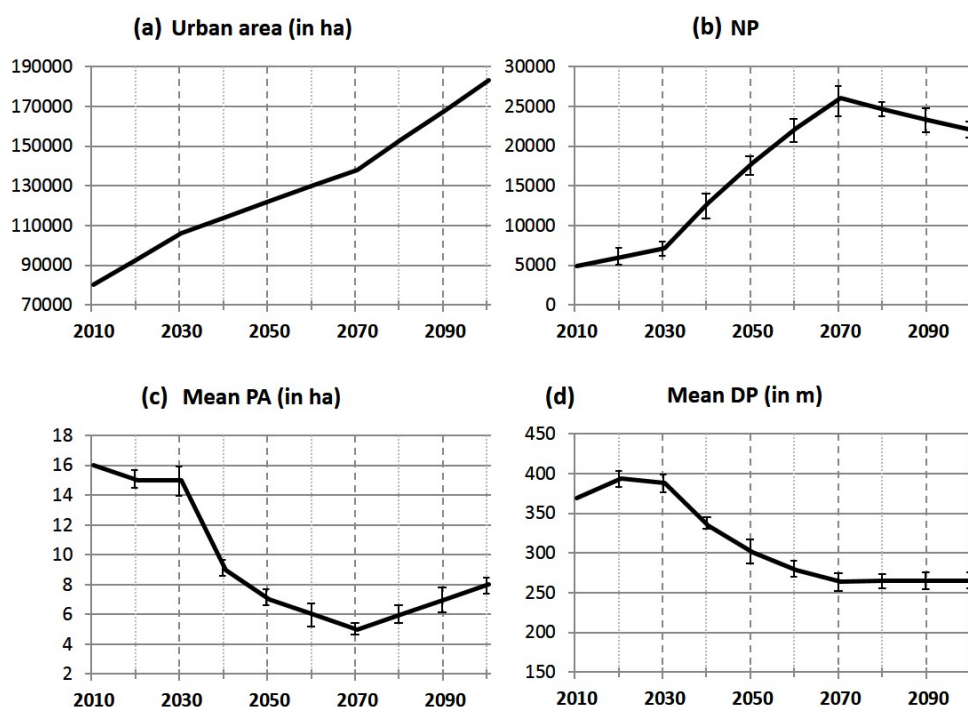


Figure 7 - Evolution of (a) the overall urban area (in ha); (b) the number of urban patches; (c) the mean urban patch size and its standard deviation; (d) the mean distance between urban patches and its standard deviation.



The error bars illustrate the mean deviation for the concerned indicators computed from the 30 simulations made.

Application of SLEUTH* for contrasting future scenarios

Experiments

- 28 Several scenarios have been built using an original method coupling participative and modeling approaches within the ACCLIMAT modeling platform (Masson et al, 2014). The scenarios defined then combine both normative assumptions from narratives (defining which kind of urban form we want to? move forward and/or the occurrence of socio-economic crises for example) and forecasting trends simulated by an economic model (of population growth for example) (Marchadier et al, 2012). The participatory approach involved scientists, experts, urban planners and decision makers and led to the definition of seven future scenarios. Only three are presented here and explore contrasting futures of Toulouse’s metropolitan growth for 2100.
- 29 The first one (called ‘*Passive*’) projects current trends: Toulouse remains one of the most attractive metropolitan areas in France accordingly to the demographic projections made by the French Institute of Economic and Demographic Statistics; decision makers fail to build a common vision for the metropolitan area and each mayor helps only the development of their own municipality, leading only to the preservation of the existing natural areas of 2010 (Excluded map E1 - Fig 2b); urbanization patterns pursue the observed trends since 1990 and exhibit identical values as those described in §2.3.1.; urban density is low with a “floor surface built /garden” (Fg) ratio equal to 0.14 (i.e. for 100 square meters of floor surface, 700 square meters of garden, roads and car park are built).
- 30 The second scenario (called ‘*Green*’) favors the development of a multipolar urban area in 2100, where some satellite municipalities of Toulouse selected in 2040 concentrate most new arrivals to preserve recreational areas and agriculture (Excluded map E3 - Fig. 4e). Urban growth is authorized only in nearby existing urban areas. The demographic trend is similar to the previous scenario. The urban density increases over the simulation period with a “floor surface built /garden” ratio of 0.25 until 2040 and 0.5 after 2040.
- 31 The third scenario (called ‘*Reactive*’) is founded on the goal of a compact metropolitan area by 2100: a green belt is defined in 2040 to limit urban sprawl (Excluded map E2 - Fig. 4d).

Unfortunately, in this scenario local authorities did not anticipate the peak oil crisis occurring in 2040 and the main industries (aeronautics and space industries) are particularly affected. The demographic projection expects a decrease of Toulouse’s attractiveness by 2040, exhibiting a loss of inhabitants after 2070. The urban density is low over the 2010-2040 period ($F_g = 0.14$) but increases after 2040 ($F_g = 0.25$).

32 In summary, the three contrasting scenarios *passive*, *green* and *reactive* city were built using contrasting normative / forecasting assumptions concerning demographic trends and urban planning strategies. These strategies are dedicated to defining the urban growth processes, the overall urban form (compact, spread or multipolar) of the Toulouse metropolitan area and the mean household density (F_g) used as inputs for the coupling of SLEUTH* with an economic model. Hence, based on these scenarios and their related assumptions, the Non-Equilibrium-Dynamical Urban Model (NEDUM – Gusdorf and Hallegatte, 2007; Gusdorf et al, 2008) was used to estimate the urban growth. NEDUM driven by economic considerations and general laws that make the model robust and suitable for long-term simulations⁵. For its use over the next century, NEDUM has been validated over the past century (Viguié et al, 2014). However, the model exhibits some limitations in simulating small-scale details (e.g. the urban concentration due to local amenities, urban growth processes and patterns). Hence, when dynamically coupled with SLEUTH* (see Masson et al, 2014 for more details), it provides data that are particularly valuable: (1) the quantity of floor surface built for residential housing and the total newly urbanized areas (roads, garden, etc.) which are added to the urbanized area in hectares based on the scenarios’ assumptions of F_g ; (2) a rent price map expressing the attractiveness of the urban area for the new inhabitants. Both data are computed at a decadal (10 years) time-step and dynamically coupled with SLEUTH*. For the *reactive* scenario, NEDUM expects a loss of population leading to negative rates of urban growth. It is assumed that it leads to building abandonment and thus, negative growth values are automatically set to 0 in SLEUTH*. The dynamics of urban growth for these three scenarios are illustrated by simulated urban maps and various spatial metrics over the 2010-2100 period: the number of urban patches, the mean urban patch area and the mean distance between urban patches.

Table 3 - Summary of the application experiments. The inputs parameters of SLEUTH* are described for each simulation / scenario. Cited excluded and attractiveness maps are described in figure 4.

Objective / Simulation	Time periods	Urban growth patterns (in %)				Quantity of urbanization (in ha/year)	Excluded map	Attractiveness map
		Spontaneous	New spread centers	Edge	Road influenced			
Simulating contrasted future scenarios								
Passive	2010-2100	3	11	83	3	Dynamic*	E1	Fig. 4e **
Green	2010-2040	1	6	92	1	Dynamic*	E2	Fig. 4e **
	2040-2100	1	1	98	0		E3	
Reactive	2010-2040	3	11	83	3	Dynamic*	E1	Fig. 4e **
	2040-2070	1	6	92	1		E2	
	2070-2100	1	6	92	1		E2	

* Dynamic quantity of urbanization means that it is given dynamically by an external economic model (NEDUM) for each decadal periods – the cumulative amount of newly urbanized areas are presented in figure 4f. ** Fig 4e illustrates the attractiveness map given dynamically by the external economic model (NEDUM) for each decadal period (not shown – but similar to maps A1, A2 and A3 – Fig 2 and Fig 4). These maps integrate the feedback effects of newly urbanized areas during the preceding period.

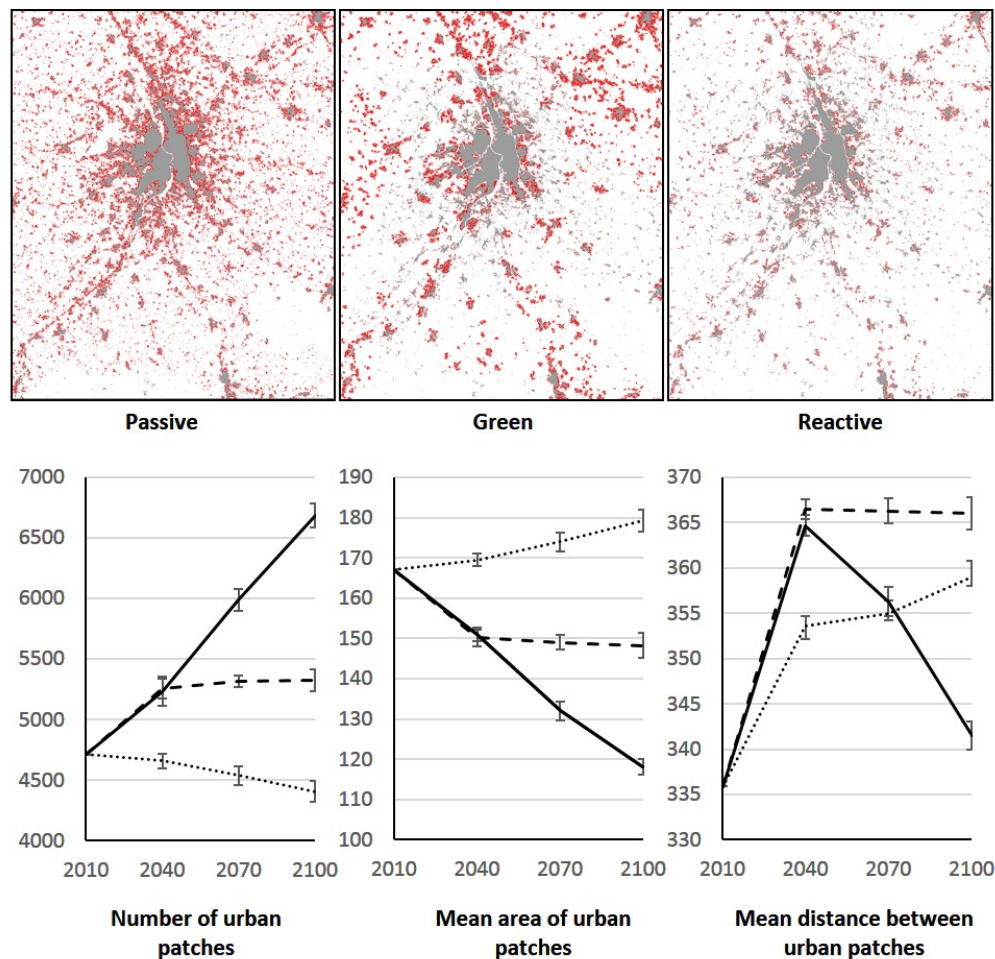
Simulating long-term contrasting scenarios

33 The Toulouse urban area exhibits three contrasting futures for 2100 according to the defined scenarios (Fig. 8a, b and c).

34 Even if the edge growth process is dominant (83%) compared to the others parameters in the *passive* scenario, the urban form is characterized by an increase of scattered urban patches (+41% compared to 2010 – Fig. 8d) with the mean size decreasing from 170 ha in 2010 to 119 ha in 2100 (Fig. 8e). The increase of the mean distance between urban patches illustrates a dispersive growth from 2010 to 2040. Then it reaches a threshold beyond which it shows

a densification of the scattered urban patches (Fig. 8f). Considering that the *passive* scenario projects current urban planning norms defined by stakeholders and aiming at controlling the scattered urban sprawl, results show that these norms are not efficient to reach this objective. Unlike the *passive* scenario, the restrictions implemented in the *green* scenario promote a multipolar urban area that minimizes the effect on the attractiveness of the central city. The decrease in the number of urban patches (-6% compared to 2010 - Fig. 8d) and the increase of their mean size (+7% - Fig. 8e) mean that urbanization derives from the growth of existing municipalities of medium size. Hence, the urban strategies (i.e. control of urban patterns and excluded areas) defined in the *green* scenario are consistent to reach a multipolar urban form. Finally, if the previous results appear consistent in terms of urban form with what one could expect from the spatially explicit simulation of this scenario, this is not so obvious with the *reactive* scenario. This scenario illustrates a reaction by decision makers, occurring in 2040, towards addressing the inefficiency of current urban planning strategies. While new strategies aimed at moving towards a more compact urban area, the simulated map for 2100 (Fig. 8c) shows the ineffectiveness of the green belt and the limitation of scattered urban patches. The number, the mean area and the mean distance between urban patches remain approximately constant after 2040 (Fig. 8d, e and f) illustrating the influence of the crisis occurring at the same period. Even if decision makers have been reactive in managing their urban areas according to a common vision, the lack of anticipation of global socio-economic events and their related regional effects lead to inefficient urban policies. Another scenario (not shown here), combining the demographic trends of the two previous scenarios with the *reactive* one, illustrates inversely their efficiency but only for a 20-30 year period. Because the green belt footprint has not been modified between 2040 and 2100, the growth leads to new urbanized areas farther away, illustrating an unexpected consequence of the green-belt.

Figure 8 - Simulation of urban growth (in red) compared to the urban extent in 2010 (in grey) for three contrasting scenarios. Evolution over the simulation period 2010-2100 of the evaluation criteria for the passive (plain line), the green (dot line) and the reactive (dash line) scenarios. The error bars illustrates the mean deviation computed from the 30 simulations made.



Discussion

37 Based on the non path-dependent approach that we defined and adopted, we next discuss the SLEUTH* parameterization and its advantages and limitations compared to the existing version of SLEUTH.

SLEUTH* parameterization and validation

38 We assumed that a well calibrated model (using past statistics and/or input data) would not be properly adapted for simulating breaking trends future scenarios, defined as disruptions with past trends in terms of land demand, urban change patterns and allocations due to non-stationary weights of driving forces. Based on these assumptions, how can a model be validated? How can these performances be evaluated? Even if this critical issue has not been directly answered, the originality of this paper comes from the proposed validation framework which combines three experiments and multiple evaluation indices. The combination of these experiments is crucial for improving the level of confidence that users or stakeholders have in the model's capabilities to simulate scenario-based LUCC changes. Taken independently, these experiments may appear odd or even trivial or tautological. But, if the model is able to simulate past changes, it does not automatically mean that it is able to simulate future scenario-based changes that did not occur yet in the past. Moreover, we hypothesize that conventional validation tools (Paegelow et al, 2014) are consistent for validating the use of a model within a prospective approach (Houet et al, 2014; Houet, 2015) if several of them are combined. A single tool may not be appropriate to evaluate all the experiments. Concerning the model calibration, we could have used the original version of SLEUTH to

calibrate the input parameters. It would have helped to improve SLEUTH* performance but for the first experiment only. However, for the sake of demonstration, we used only empirically-based parameters (as they would be defined during the scenarios’ construction) that did show convincing results. Moreover, the use of such simple parameters seems to have facilitated the understanding of the model’s functioning. When considering that assessing the simulation of the future of urban change is not possible, it may slightly balance the level of requirements that modelers may have for the input parameters. The more precise the input data, the more confident the users are in the resulting simulations. The final point concerns the robustness of the results. As shown in table 4, figures 7 and 8, small variations can be observed from the 30 simulations made. They inherit from the stochastic allocation processes. Results show that randomness does not affect the trajectories of scenario-based urban changes are helpful to improve the confidence users can have in the model outcomes.

- 39 Two points concerning the model parameterization can also be discussed. The first concerns the influence of the attractiveness map. Results obtained from the simulation of past urban evolution show some controversial effects of this optional additional factor. If it improves the global accuracy of correctly predicted urban growth, it also slightly reduces the model’s ability to simulate the overall urban pattern. The visual comparison of difference maps (Fig. 5a and 5b) helps to understand this: the attractiveness map (rent price map) improved the allocation of urban growth within the central part of the urban area. The integration of the economic driving factor is particularly valuable. Conversely, when this additional factor is disabled, SLEUTH* performs better in the surrounding municipalities, increasing the accuracy of forecasting urban pattern. Better performance could have been obtained by tuning the growth parameters, whose relative contributions may differ if using this optional map. However, the aim was to assess model performance using similar parameters values that can be derived from various simple – GIS, expert-based or scenario-based – approaches as shown with the other two experiments.
- 40 The second point, which is closely related to the first one, concerns the various ways that SLEUTH* can be used. The SAS approach requires it to be simple and flexible when used within a participatory framework, as well as sophisticated when tightly coupled with other models. Hence, even if some parameters are empirically calibrated, the resulting simulations still provide valuable urban maps. Indeed, the experience of the ACCLIMAT project shows that results for the simulation of a past evolution were sufficient to improve the confidence that stakeholders have in SLEUTH*’s ability to simulate (future) urban changes (Masson et al. 2014). The illustration of the model’s ability to simulate exaggerated trend breaking urban change was even more convincing. Whatever the adopted approach used to parameterize SLEUTH* (expert-knowledge vs. model coupling), simulations show that: (1) it is possible to simulate contrasting urban futures, exhibiting trend breaking in terms of urban spatial (form, patterns) and temporal (rates) dynamics and; (2) to provide a spatial rendering that is consistent with the predefined scenarios.

Advantages and drawbacks: SLEUTH* vs. SLEUTH

- 41 The technical developments made on SLEUTH* are not sufficient to pretend that this version of SLEUTH strongly differs from the original, although they were necessary to impose a non path-dependent approach. The main difference between them was the way that they are used and parameterized for exploring the future: SLEUTH is valuable for exploring future urban trends of urban dynamics, based on a robust calibration phase, coupled or not with the various urban planning strategies. SLEUTH* performs well in simulating contrasting scenarios of urban changes based on normative and/or forecasting assumptions, within a participatory framework or coupled with external models. Hence, the main advantages and drawbacks of both the SLEUTH and SLEUTH* models are listed in table 3. The SLEUTH* version answers some of the limitations listed in the introduction and does not aim at replacing SLEUTH since it is complementary.

Table 3 - Comparison of respective advantages and drawbacks of SLEUTH and SLEUTH*

	SLEUTH (cf. cited references)	SLEUTH* (cf. this paper)

Model objectives / abilities		
Simulating a past evolution	Yes The model calibration and the auto-adaptation of growth parameters (using landscape patterns indices) allow the simulation over several centuries with high accuracy. (Clarke and Gaydos 1998; Dietzel and Clarke 2004)	Yes Probably limited to a short period (10-20 years) due the empirically defined growth parameters.
Simulating trends breaking urban changes	No / (Yes?) Auto-adaptive growth parameters allow the simulation of trend breaking of the urban patterns, with no disruptions in the land demand. Auto-adaptation is by self-modification. (Clarke and Gaydos 1998)	Yes Users empirically control the contribution of each parameters (land demand, growth parameters...) over user-defined sub-periods
Simulating various urban planning strategies	Yes (Jantz et al 2003; ; Mahiny and Clarke, 2012)	Yes
Simulating various types of scenarios	No Mainly dedicated to simulate forecasting / trends scenarios	Yes Adapted to simulate narratives, normative and forecasting scenarios
Potential use for participatory approaches	Limited (cf. Gigalopolis project*) Main limitations concern the GIS database preparation. The calibration is time consuming. (Suarez-Rubio et al, 2012)	Yes (cf. ACCLIMAT project**) Main limitations concern the GIS database preparation. Its use does not require any experience in LUCC modeling due to the interface. Instantaneous results.
Model parameterization and performance		
Input requirements (Main differences)	Minimum of four urban maps	One urban map Pre-defined scenario(s)
Land demand (Estimation of the amount of urban changes)	Model estimation made during the calibration phase	Defined by users (scenario) or external model
Urban growth (Estimation of contributing urban patterns)	Model estimation made during the calibration phase. Auto-adaptation regarding the simulated urban growth. Reproduction / Extrapolation of past trends patterns	Defined by users (scenario) Definition of contrasted patterns over various sub-periods
Controlling urban form (Definition of protected areas)	Controlled by user-defined excluded map.	Controlled by user-defined excluded map. Several maps can be considered by the model over the simulation
Weighting constraints of urban planning (Definition of attractive / repulsive areas)	Controlled by user-defined excluded map using real values (Jantz et al, 2010; Mahiny and Clarke, 2012)	Controlled by user-defined attractiveness map. Several maps can be considered by the model over the simulation
Transportation (Definition of road influence: network and distance)	Controlled by user-defined transportation map. Several maps can be considered by the model over the simulation. Road gravity is defined by users and fixed over the simulation.	
Influence of terrain	Integrated through the slope coefficient and the critical slope (Clarke et al 1997)	
Computational time	The calibration phase is time consuming while the simulation of urban maps is fast	The simulation of urban maps is fast (1 min for 90 years with iCore 5, 2 GHz)

* <http://www.ncgia.ucsb.edu/projects/gig/>** <http://www.cnrm.meteo.fr/ville.climat/?lang=en>

Conclusion

42 This research distinguished two approaches for coupling future scenarios and LUCC models depending on how path-dependent they need to be. This distinction is based on the method used to build the scenarios. When assuming the path-dependency of the approach, LUCC models are part of the method. In the non path-dependent approach, conventional scenario-based methods can be performed and LUCC models are thus used to spatially explicitly render them using advanced techniques to refine the allocation of LUCC. Some LUCC models have limitations for their use for the latter as they strongly depend on past trends and inputs. We used and slightly modified (calibration disabled, addition of a geographic layer) an existing urban model (SLEUTH) in order to adapt it for such an approach (SLEUTH*). Results demonstrated its performance at simulating trend breaking urban dynamics and contrasting future scenarios, based on normative and forecasting assumptions, defined by a participative framework and model coupling. Nevertheless, it questions the validation procedure of such models and this paper proposes one that needs to be further experimented, improved and discussed.

Bibliographie

- Alonso W (1964) *Location and Land Use: Toward a General Theory of Land Rent*. Harvard University Press, Cambridge (MA, USA).
- Alcamo J (2008) Environmental futures: the practice of environmental scenario analysis. Developments in Integrated Environmental Assessment—Volume 2. Elsevier, Amsterdam
- Amer M, Daim TU, Jetter A, 2013, A review of scenario planning. *Futures*, 46, 23–40.
- Agarwal C, Green GM, Grove JM, Evans TP, Schweik CM, 2002, *A review and assessment of land-use change models: dynamics of space, time and human choice*. USDA Forest Service, Gen. Tech. Rep. NE-297. http://nrs.fs.fed.us/pubs/gtr/gtr_ne297.pdf
- Aguejdad R, Hidalgo J, Doukari O, Masson V, Houet T, 2012, *Assessing the influence of long term urban growth on urban climate*. 6th International Congress on Environmental Modeling and Software, July 1–5, 2012, at the UFZ in Leipzig, Germany
- Bishop P, Hines A, Collins T, 2007, The current state of scenario development: an overview of techniques, *Foresight*, 9, 5–25.
- Brown, D.G., Page, S., Riolo, R., Zellner, M., Rand, W., 2005. Path dependence and the validation of agent-based models of land use. *International journal of geographical information science*, 19(2), 153-174.
- Candau J, Rasmussen S, Clarke KC, 2000, *A coupled cellular automaton model for land-use / land cover dynamics*, Proceedings of the 4th International Conference on Integrating GIS and Environmental Modeling (GIS/EM4): Problems, Prospects and Research Needs, Banff, Alberta, Canada, 2–8 September <http://www.colorado.edu/research/cires/banff/pubpapers/94/>
- Candau JC, 2002, *Temporal Calibration Sensitivity of the SLEUTH Urban Growth Model*. M.A. Thesis. University of California, Santa Barbara.
- Chaudhuri G, Clarke KC, 2013, The SLEUTH land use change model: A review. *The International Journal of Environmental Resources Research*, 1(1), 88-104.
- Claggett P, Jantz CA, Goetz SJ, Bisland C, 2004, Assessing development pressure in the Chesapeake Bay watershed: An evaluation of two land-use change models. *Environmental Monitoring and Assessment*, 94, 129-146
- Clarke KC, Hoppen S, Gaydos L, 1997, A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area. *Environment and Planning B*, 24, 247-261
- Clarke KC, Gaydos L, 1998, Loose-coupling a cellular automaton model and GIS: Long-term urban growth prediction for San Francisco and Washington/Baltimore. *International Journal of Geographic Information Science*, 12, 699–714
- Clarke KC, Gazulis N, Dietzel CK, Goldstein NC, 2007, A decade of SLEUTHing: Lessons learned from applications of a cellular automaton land use change model. Chapter 16. In: Fisher, P. (ed). *Classics from IJGIS. Twenty Years of the International Journal of Geographical Information Systems and Science*. Taylor and Francis, CRC. Boca Raton, FL. 413-425

- Clarke KC, 2008, A Decade of Cellular Urban Modeling with SLEUTH: Unresolved Issues and Problems, Chapter 3. In: Planning Support Systems for Cities and Regions (Ed. Brail, R. K., Lincoln Institute of Land Policy, Cambridge, MA, 47-60, http://www.ncgia.ucsb.edu/projects/gig/Pub/SLEUTHPapers_Nov24/Clarke_Lincoln2008.pdf
- Clergeau P, Croci S, Jokimaki J, Kaisanlahti-Jokimaki M, Dinetti M, 2006, Avifauna homogenisation by urbanisation: analysis at different European latitudes. *Biological Conservation*, 127, 336-344.
- Dietzel CK, Clarke KC, 2004, Determination of optimal calibration metrics through the use of self-organizing maps. Proceedings of the Integrated Assessment of the Land System Workshop. October 28-30, 2004. Institute for Environmental Studies, Amsterdam
- Dietzel C, Herold M, Hemphill JJ, Clarke KC, 2005, Spatio-temporal dynamics in California's Central Valley: Empirical links to urban theory. *International Journal of Geographic Information Science*, 19(2), 175-195
- El Abidine El Morjani Z, Ebener S, Boos J, Abdel Ghaffar E, Musani A, 2007, Modeling the spatial distribution of five natural hazards in the context of the WHO/EMRO Atlas of Disaster Risk as a step towards the reduction of the health impact related to disasters, *International Journal of Health Geographics*, 6(8)
- Forys E, Allen CR, 2005, The impacts of sprawl on biodiversity: the ant fauna of the lower Florida Keys. *Ecology and Society* 10(1), 25, <http://www.ecologyandsociety.org/vol10/iss1/art25/>
- Gaucherel C, Alleaume S, Hély C, 2008, The Comparison Map Profile method: a strategy for multiscale comparison of quantitative and qualitative images. *IEEE Transactions on Geoscience and Remote Sensing*, 46 (9), 2708-2719.
- Godet M, 1986, Introduction to 'la prospective': seven key ideas and one scenario method. *Futures*, 18, 134-157
- Goldstein NC, 2004, *Brains vs. brawn – Comparative strategies for the calibration of a cellular automata-based urban growth model*. In: P. Atkinson, G. Foody, S. Darby, and F. Wu., (eds). GeoDynamics, Boca Raton, CRC Press.
- Goldstein N, Dietzel C, Clarke K, 2005, *Don't Stop 'Til You Get Enough - Sensitivity Testing Of Monte Carlo Iterations For Model Calibration*, Proceedings, 8th International Conference on GeoComputation. <http://www.geocomputation.org/2005/Goldstein1.pdf>
- Gusdorf F, Hallegatte S, 2007, Compact or Spread-Out Cities: Urban Planning, Taxation, and the Vulnerability to Transportation Shocks. *Energy Policy*, 35, 4826-4838
- Gusdorf F, Hallegatte S, Lahellec A, 2008, Time and space matter: how urban transitions create inequality. *Global Environment Change*. 18(4), 708-719
- Gustafson EJ, 1998, Quantifying landscape spatial pattern: What is the state of the art? *Ecosystems*. 1(2), 143-156
- Haase D, Shwarz N, 2009, Simulation Models on Human-Nature Interactions in Urban Landscapes: A Review Including Spatial Economics, System Dynamics, Cellular Automata and Agent-based Approaches. *Living Reviews in Landscape Research*, 3(2) <http://www.livingreviews.org/lrlr-2009-2>
- Houet T, Gaucherel C, 2007, Simulation dynamique et spatialement explicite d'un paysage agricole bocager: Validation sur un petit bassin versant breton sur la période 1981-1998. *International Journal of Geomatics and Spatial Analysis*, 17(3-4), 491-516
- Houet T, Loveland TR, Hubert-Moy L, Gaucherel C, Napton D, Barnes CA, Sayler KL, 2010, Exploring subtle land use and land cover changes: a framework for future landscape studies, *Landscape Ecology*, 25(2), 249-266
- Houet T, Pigeon G, 2011, Mapping urban climate zones and quantifying climate behaviors - An application on Toulouse urban area (France), *Environmental Pollution*, 159(8-9), 2180-2192
- Houet T., Schaller N., Castets M., Gaucherel C., (2014) Improving the simulation of fine scale landscape changes coupling top-down and bottom-up land use and cover changes rules. *International Journal of Geographical Science*, 28(9), 1848-1876
- Houet T. (2015), Usages de modèles spatiaux pour la prospective, *Revue Internationale de Géomatique*, Vol. 25/1, pp. 123-143
- Jantz CA, Goetz SJ, Shelley MK, 2003, Using the SLEUTH urban growth model to simulate the impacts of future policy scenarios on urban land use in the Baltimore/Washington metropolitan area. *Environment and Planning B*, 31, 251-71

- Jantz CA., Goetz CJ., Donato D, Claggett P, 2010, Designing and implementing a regional urban modeling system using the SLEUTH cellular urban model. *Computers, Environment and Urban Systems*, 34, 1-16
- Johnson MP, 2001, Environmental impacts of urban sprawl: a survey of the literature and proposed research agenda. *Environment and Planning A*, 33(4), 717-735
- Kolb M, Mas JF, Galicia L, 2013, Evaluating drivers and transition potential models in a complex landscape in southern Mexico. *International Journal of Geographical Information Science*. 27(9), 1804-1827
- Kok K, Verburg P, Veldkamp T, 2007a, Integrated Assessment of the land system: The future of land use. *Land use policy*, 24(3), 517-520
- Kok, K., Biggs, R. and Zurek, M., 2007b. Methods for developing multiscale participatory scenarios: insights from southern Africa and Europe [online]. *Ecology and Society*, 13(1), 8. Available from: <http://www.ecologyandsociety.org/vol12/iss1/art8/> [Accessed July 2013]
- Lambin EF, Geist HJ, 2006, *Land-Use and Land-Cover Change – Local processes and Global impacts, Global Change – The IGBP Series*, Ed. Springer.
- Landis J.D., 1998, *Development and pilot application of the California Urban and Biodiversity Analysis (CURBA) Model*, Coll. Monograph, University of California, Berkeley. Institute of Urban & Regional Development, p. 77
- Mahiny AS, Clarke K, 2012, Guiding SLEUTH land-use / land-cover change modeling using multicriteria evaluation: towards dynamic sustainable land-use planning. *Environment and Planning B: Planning and Design*. 39, 925-944
- Marchadier C, Houet T, Bretagne G, 2012, *How to define and assess city adaptation strategies?* ICUC8 - 8th International Conference on Urban Climate – ICUC 8 and 10th Symposium on the Urban Environment, August 6-10, 2012, Dublin, Ireland.
- Mas JF, Kolb M, Paegelow M, Camacho Olmedo MT, Houet T, 2014, Modeling Land use / cover changes: a comparison of conceptual approaches and softwares. *Environmental Modeling and Software*, 51, 94-111
- Masson V, Gomes L, Pigeon G, Lioussé K, Lagouarde JP, Voogt J, Salmond J, Oke T, Legain D, Garrouste O, Tulet P, 2008, The canopy and aerosol particles interactions in Toulouse urban layer (CAPITOL) experiment. *Meteorology and Atmospheric Physics*, 102 (3-4), 135-157.
- Masson V, Marchadier C, Adolphe L, Aguejda R, Avner P, Bonhomme M, Bretagne G, Briotter X, Bueno B, de Munck C, Doukari O, Hallegatte S, Hidalgo J, Houet T, Lemonsu A, Long N, Moine MP, Morel T, Nolorgues L, Pigeon G, Salagnac JL, Zibouche K, 2014, Adapting Cities to Climate change: a systemic modeling approach, *Urban Climate*. 10(2), 407-429.
- McGarigal K, Marks BJ, 1995, *FRAGSTATS: spatial pattern analysis program for quantifying landscape structure*. General Technical Report PNW-GTR-351, USDA Forest Service, Pacific Northwest Research Station, Portland, OR.
- Mills, E.S. (1967) An aggregative model of resource allocation in a metropolitan area. *American Economy Review*, 57, 197–210.
- Muth R.F. (1969) *Cities and Housing; the Spatial Pattern of Urban Residential Land Use*. University of Chicago Press, Chicago (USA).
- Onsted JA, 2002, *SCOPE: A modification and application of the Forrester Model to the South Coast of Santa Barbara County*. Master's Thesis, Department of Geography, University of California – Santa Barbara.
- Onsted JA, 2007, *Effectiveness of the Williamson Act: A Spatial Analysis*. PhD Dissertation, Department of Geography, University of California, Santa Barbara.
- Paegelow M., Camacho Olmedo M.T., Mas J.F., Houet T., (2014) Benchmarking of LUCC modeling tools by various validation techniques and error analysis, *Cybergeo*, n°701, <http://cybergeo.revues.org/26610>
- Pontius RG, 2000, Quantification error versus location error in comparison of categorical maps. *Photogrammetric Engineering of Remote Sensing*, 66(8), 1011–1016
- Pontius RG, 2002, Statistical methods to partition effects of quantity and location during comparison of categorical maps at multiple resolutions. *Photogrammetric Engineering of Remote Sensing*, 68(10), 1041–1049
- Pontius RG, Boersma W, Castella JC, Clarke K, de Nijs T, Dietzel C, Duan Z, Fotsing E, Goldstein N, Kok K, Koomen E, Lippitt CD, McConnell W, Sood AM, Pijankowski B, Pidhadia S, Sweeney S, Trung

- TN, Veldkamp AT, Verburg PH, 2008, Comparing the input, output, and validation maps for several models of land change. *Annals of Regional Science*, 42(1), 11-27
- Price B, Kienast F, Seidl I, Ginzler C, Verburg P, Bolliger J (2014) Future landscapes of Switzerland: Risk areas for urbanisation and land abandonment, *Applied Geography*, 57, 32-41
- Silva EA, Clarke KC, 2002, Calibration of the SLEUTH urban growth model for Lisbon and Porto, Portugal. *Computers, Environment and Urban Systems*, 26, 525-52
- Silva EA, Clarke KC, 2005, Complexity, emergence and cellular urban models: Lessons learned from applying SLEUTH to two Portuguese cities. *European Planning Studies*, 13, 93-115
- Solecki WD, Oliveri C, 2004, Downscaling climate change scenarios in an urban land use change model. *Journal of Environmental Management*, 72, 105-115
- Suarez-Rubio M, Lookingbill TR, Wainger LA, 2012, Modeling exurban development near Washington, DC, USA : comparison of a pattern-based model and a spatially-explicit econometric model. *Landscape Ecology*, 27, 1045-1061
- Tu J, Xia ZG, Clarke K, 2007, Impact of Urban Sprawl on Water Quality in Eastern Massachusetts, USA. *Environmental Management*, 40(2), 183-200
- Turner B, Lambin E, Reenberg A, 2007, The emergence of land change science for global environmental change and sustainability. *Proceedings of the National Academy of Science of the USA*, 104(52), 20666-20671
- United Nations, 2012, *World Urbanization Prospects, the 2011 Revision: Highlights*. United Nations, Department of Economic and Social Affairs, Population Division, New York, 2012 –http://esa.un.org/unpd/wup/pdf/WUP2011_Highlights.pdf
- Verburg P, Schot P, Djst M, Veldkamp T, 2004, Land use change modeling: current practices and research priorities, *GeoJournal*, 61(4), 309-324
- Verburg P, Van Berkel D, Van Doorn A, Van Eupen E, Van den Heiligenberg H, 2010, Trajectories of land use change in Europe: a model-based exploration of rural futures. *Landscape Ecology*, (25)2, 217-232
- Verburg P, Eickhout B. and van Meijl H., (2008) A multi-scale, multi-model approach for analyzing the future dynamics of European land use, *Annals of Regional Science*, 42 (1) (2008), pp. 57-77
- Viguié V, Hallegatte S, Rozenberg J, 2014, Downscaling long term socio-economic scenarios at city scale: a case study on Paris, *Technological forecasting and social change*, 87, 305-324
- Xiang WN, Clarke KC, 2003, The use of scenarios in land –use planning. *Environment and Planning B; Planning and Design*. 30, 885-909
- Yang X, Lo CP, 2003, Modeling urban growth and landscape change in the Atlanta metropolitan area. *International Journal of Geographical Information Science*, 17, 463-488
- Wack P, 1985a, Scenarios: uncharted waters ahead, *Harvard Business Review*, 63, 73-89
- Wack P, 1985b, Scenarios: shooting the rapids, *Harvard Business Review*, 63, 139-150
- White R, Engelen G, Uljee I, 1997, The Use of Constrained Cellular Automata for High-resolution Modelling of Urban Land Use Dynamics. *Environment and Planning B: Planning and Design*, 24, 323-343.
- White R, Engelen G, 1993, Cellular Automata and Fractal Urban Form: A Cellular Modelling Approach to the Evolution of Urban Land Use Patterns. *Environment and Planning A*, 25, 1175 - 1199.

Notes

1 The bridging function of a scenario permits and encourages communication between people from two different communities of modeling and planning. The scenarists, usually specialists, share their knowledge, expertise, convictions, and insights with the often non specialist scenario users. The scenario users, usually stakeholders, policymakers, the general public, and planning practitioners, reciprocate by bringing real-world relevance into modeling exercises and by setting up the ultimate benchmarks for composing quality scenarios and the standards for selecting and validating models. (cited from Xiang and Clarke, 2003)

2 <http://www.cnrm.meteo.fr/ville.climat//spip.php?rubrique47>

3 Contact the corresponding author or go to: http://w3.geode.univ-tlse2.fr/modele_formulaire_sleuth.php

4 A new version is currently being developed in order to automatically integrate new input maps during simulation.

5 NEDUM-2D is a dynamic model which relies on the classical urban economics framework, an economic modeling approach developed since the end of the 1960s (Alonso 1964 ; Mills 1967; Muth 1969) which explains the spatial distribution – across the city – of the costs of land and of real estate, housing surface, population density and building heights and density. As explained in Gusdorf et al. (2008), urban economics has been mostly used to explore the characteristics of long run equilibriums. However, the existence of urban stationary equilibriums is questionable: when population, transport prices, or income vary, housing infrastructure cannot adapt rapidly to changing conditions and is always out of equilibrium. This is the reason why the model takes explicitly into account this dynamics and describes cities as non-equilibrium systems (cited from Viguié et al 2014).

Pour citer cet article

Référence électronique

Thomas Houet, Rahim Aguejdad, Omar Doukari, Guillaume Battaia et Keith Clarke, « Description and validation of a "non path-dependent" model for projecting contrasting urban growth futures », *Cybergeo : European Journal of Geography* [En ligne], Systèmes, Modélisation, Géostatistiques, document 759, mis en ligne le 06 janvier 2016, consulté le 07 janvier 2016. URL : <http://cybergeo.revues.org/27397> ; DOI : 10.4000/cybergeo.27397

À propos des auteurs

Thomas Houet

UMR GEODE 5602 CNRS, Université Toulouse le Mirail, 5 allée Antonio Machado, 31058 Toulouse
Chargé de recherche CNRS
thomas.houet@univ-tlse2.fr

Rahim Aguejdad

UMR LIVE 7362 CNRS, Université de Strasbourg, 3 rue de l'Argonne, 67000 Strasbourg
Chargé de Recherche CNRS
rahim.aguejdad@live-cnrs.unistra.fr

Omar Doukari

Ecole Spéciale des Travaux Publics, du Bâtiment et de l'Industrie (ESTP Paris), Campus de Cachan,
28 avenue du Président Wilson - 94234 Cachan Cedex
Enseignant-chercheur
odoukari@estp-paris.eu

Guillaume Battaia

Toulouse Tech Transfer, Maison de la Recherche et de la Valorisation (MRV), 118 route de Narbonne,
CS 24246 - 31432 Toulouse cedex 4
Ingénieur valorisation
battaia@toulouse-tech-transfer.com

Keith Clarke

University of California, Santa Barbara, Department of Geography, 1720 Ellison Hall, Santa Barbara,
CA 93106-4060
Professor
kclarke@geog.ucsb.edu

Droits d'auteur

© CNRS-UMR Géographie-cités 8504

Résumés

This paper presents a model (SLEUTH*) for projecting contrasting urban growth futures. It is derived from the SLEUTH model, which has been modified in order to incorporate an additional spatially explicit factor, and to be used in a fully controlled forecasting mode. Our aim is to spatially allocate urban growth, its amount and pattern, according to predefined prospective scenarios and assuming a non path-dependency approach. This modelling approach aims at being used under a "story and simulation" (SAS) approach, which

constrains the model validation. To assess model efficiency, three types of tests have been undertaken: (1) sensitivity tests; (2) reproduction of known changes over a past period; and (3) simulation of changes that break trends. Results show that SLEUTH* conveniently simulates expected urban changes for exploring contrasting scenarios that are the basis for land planning strategies.

Description et validation d'un modèle indépendant des trajectoires d'évolution passées pour simuler des futures contrastées de l'étalement urbain

Cet article présente un modèle de simulation spatiale (SLEUTH*) dédié à la projection de scénarios contrastés d'étalement urbain. Il hérite du modèle SLEUTH et les modifications apportées visent à intégrer un facteur additionnel de localisation des changements et à l'utiliser de façon contrôlée pour simuler ces projections. Le but est de pouvoir distribuer spatialement la croissance urbaine, en termes de superficie et de motif spatial, conformément à la définition de scénarios prospectifs normatifs afin de pouvoir les simuler dynamiquement. Ce modèle suppose donc d'être indépendant vis-à-vis des trajectoires passées afin d'être utilisé suivant une approche « récit et simulation ». Ce type d'approche engendre certaines contraintes pour la validation du modèle. Pour évaluer la performance du modèle, trois types de tests ont été réalisés : (1) des tests de sensibilité ; (2) la reproduction de changements observés sur une période passée ; et (3) démontrer son aptitude à simuler des ruptures dans les dynamiques d'étalement urbain. Les résultats montrent que SLEUTH* simule convenablement les changements (passés ou futurs) attendus et est approprié pour simuler des scénarios contrastés qui sont la base pour définir des stratégies de planification urbaine.

Entrées d'index

Mots-clés : occupation et utilisation du sol, modèle, trajectoires, scénarios, futur tendanciel vs. contrasté, SLEUTH

Keywords : land use and land cover, model, trajectories, scenarios, trends vs. contrasting futures, SLEUTH